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The prevalence of cooling flows in early-type galaxies

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Summary. The density profiles of the hot interstellar gas in 18 galaxies, mostly ellipticals, have been determined using X-ray data from the *Einstein Observatory*. Radiative cooling is important throughout most of this gas leading to mass-deposition rates of between 0.02 and $3 M_{\odot} \text{yr}^{-1}$. There are problems in determining the nature of the resultant cooling flows since these mass-deposition rates are significantly less than the expected injection of gas from stellar mass loss, and supernova heating is not accounted for. We suggest possible solutions involving a multi-phase medium and cooling outflows.

Cooling flows in early-type galaxies have immediate implications for their chemical evolution, optical line emission, star formation, the behaviour of cold discs, the activity of the nucleus and the confinement of radio jets.

1 Introduction

Extended X-ray emission from individual elliptical galaxies was first reported by Forman *et al.* (1979). The observations of the X-ray ‘plume’ of M86, of diffuse emission from Cen A (Feigelson *et al.* 1981) and analysis of the X-ray spectra (Forman, Jones & Tucker 1985) strongly suggest that much of the emission is due to hot gas. Further work by Trinchieri & Fabbiano (1985) and by Trinchieri, Fabbiano & Canizares (1986) confirms the gas content with some reservations about its level in low-luminosity systems where point sources (e.g. X-ray binaries) may be a significant component. Forman *et al.* (1985) have studied the X-ray emission from some 55 early-type galaxies and find that most contain 10^9 – $10^{10} M_{\odot}$ of gas at temperatures 5×10^6 – 2×10^7 K. Many of these galaxies are in the Virgo cluster. Earlier work on X-rays from the relatively isolated elliptical galaxy NGC 1395, by Nulsen, Stewart & Fabian (1984), showed that any gas flows must be highly subsonic. Such cooling flows (see Fabian, Nulsen & Canizares 1984) consist of up to $1 M_{\odot}$ of gas cooling out per year in an early-type galaxy and presumably forming stars. This means that gas content and star-formation rates in early-type galaxies are similar to those in many late-type galaxies.

In this paper we analyse in some detail the *Einstein Observatory* X-ray data from the inner parts of early-type galaxies. As well as several normal elliptical galaxies, the sample includes the LINER NGC 1052, the radio galaxies NGC 315 and Fornax A, and the Sombrero galaxy. Our main objectives are the determination of the gas density profiles and the mass-deposition rates from cooling gas. In Section 2 we first discuss the systematic errors associated with the X-ray surface-brightness distributions of the galaxies. These are deprojected in Section 2.1 to give count-emissivity profiles which we convert to density profiles in Section 2.2. These are robust and are similar in form between galaxies. The short cooling times at the centre of the galaxies imply deposition of cooled material and the flow of gas within them. We find such ‘cooling flows’ in all of the galaxies.

Most theoretical work on gas flows in elliptical galaxies (e.g. Mathews & Baker 1971; Mathews & Bregman 1978; Bailey 1982; White & Chevalier 1983, 1984) has assumed that the gas is homogeneous and single phase. The mass-flow rate profiles of many cooling flows, however, suggest that small density variations are amplified by thermal instability and that inhomogeneities play a large role (Nulsen 1986; Fabian, Arnaud & Thomas 1986; Thomas 1986). The interstellar medium within early-type galaxies is complex. In Section 2.3 we consider three simple models for the mass and energy balance in the hot gas (generally the quality of the data does not warrant more parameters), and confirm that cooling flows depositing $0.02\text{--}3 M_{\odot} \text{ yr}^{-1}$ occur in all of the observed galaxies.

The gas deposited in the core of the galaxies can explain the optical emission lines seen in many, and a small flow into the centre can power any active nucleus – several of the galaxies are well-known radio sources. The gas density profile is also of relevance to the confinement of their jets, as we discuss.

2 Analysis of the data

The X-ray images were made with either the Imaging Proportional Counter (IPC) or the High Resolution Imager (HRI) in the *Einstein Observatory* (Giacconi *et al.* 1979). Maps of many of the galaxies studied here are shown by Forman *et al.* (1985). The two Fornax galaxies, NGC 1399 and 1404, were also detected by *EXOSAT* and have been discussed by Mason & Rosen (1985). Details of all the galaxies are given in Table 1. Surface-brightness profiles of each galaxy were obtained by summing the counts into annular bins about the maximum of emission. After subtraction of the background, these were corrected for vignetting. Note that most of our galaxies appear spherically symmetrical. This is to be expected since, even if the underlying galaxy is elliptical, the isopotentials which constrain the gas will be more spherical. Fabian *et al.* (1981) analysed the Perseus cluster both with and without the assumption of spherical symmetry but found little difference in the results. One of our Galaxies, NGC 4406, does show an extended plume of emission in one direction. This sector was excluded from the data set but even so this may help to explain why NGC 4406 has the lowest surface brightness slope of the sample.

The largest data set is from the IPC, the detector which is the most sensitive to extended emission of low surface brightness, due to its lower background rate. The IPC has a spatial resolution of ~ 1 arcmin which is much larger than the size of the optical galaxy cores (~ 10 arcsec). Therefore the image is broadened significantly and a simple deprojection tends to produce profiles that are too flat in the centre and too steep at a few arcmin. To investigate the effect of the spatial resolution of the IPC on the surface-brightness profiles we fit a range of models to the data. Modified power-law profiles, $[1 + (r/a)^2]^{-s/2}$, with central cores of 1, 4 and 10 arcsec, were convolved with the point response of the detector appropriate to a mean photon energy of 1.5 keV and fitted to the data, which were binned in either 20 or 24 arcsec radial annuli.

Table 1. (i) Galaxy name(s). (ii) Galaxy classification from the *Revised Shapley-Ames Catalog of Bright Galaxies* (Sandage & Tammann 1981, hereafter SA). (iii) Solar-motion corrected velocity (km s^{-1}) from the *Second Reference Catalog of Bright Galaxies* (de Vaucouleurs, de Vaucouleurs & Corwin 1976, hereafter RC2), or that of the associated group; (a) 1084 group (Davies *et al.* 1983), (b) Fornax I cluster (Jones & Jones 1980), (c) Cancer (a) cluster (Bothun *et al.* 1983), (d) Virgo cluster (Davies *et al.* 1983), (iv) Distance (Mpc) using Hubble flow and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$. (v) Effective radius (kpc) from RC2, $A_e/2$ or: $D_{25}/6$. (vi) Velocity dispersion (km s^{-1}) from the compilation by Whitmore, McElroy & Tonry (1985) or: the $L-\sigma$ relation from Terlevich *et al.* (1981). (vii) H I column, 10^{21} cm^{-2} , from Stark *et al.* (in preparation). (viii) Total B -magnitude from RC2 or: SA. (ix) Total B -luminosity $10^{10} L_\odot$ using a solar $M_B = 5.48$.

	(i) Galaxy	(ii) Type	(iii) V	(iv) Dist.	(v) r_e	(vi) σ	(vii) N_H	(viii) m_B	(ix) L_B
1	N315	E	5218	104	16.1:	273	0.90	12.2 :	22.
2	N1052	E3/S0	1458 a	28.7	4.2	204	0.14	11.21	4.2
	PKS 0238-084								
3	N1316	Sa pec	1395 b	27.9	6.2	252	0.36	9.39	21.
	ARP 154, Fornax A								
4	N1332	S0	1471	29.4	4.3	306	0.26	10.84	6.2
5	N1395	E2	1583	31.7	4.9:	249	0.26	11.18:	5.3
6	N1399	E1	1395 b	27.9	3.9	251:	0.35	10.62	6.8
	PKS 0336-35								
7	N1404	E2	1404 b	27.9	2.0	233:	0.35	10.96	5.0
8	N1600	E4	4587	91.7	15.1	323	0.44	11.62	29.
9	N2300	E3	2167	43.3	6.5:	260	0.67	11.47	7.5
	ARP 114								
10	N2563	E	4500 c	90	6.5	265:	0.61	12.92	8.6
11	N4374	E1	1019 d	20.4	5.2	296	0.12	10.11	5.9
	M84 3C272.1								
12	N4382	S0 pec	1019 d	20.4	5.9	200	0.10	9.82	7.6
	M85								
13	N4406	S0/E3	1019 d	20.4	6.9	256	0.11	9.93	6.9
	M86								
14	N4472	E1/S0	1019 d	20.4	9.8	315	0.16	9.10	15.
	M49 ARP 134								
15	N4594	Sa/Sb	963	19.3	6.3	256	0.16	8.74	18.
	M104 Sombrero								
16	N4636	EO/S0	869	17.4	5.7	217	0.13	10.29	3.6
17	N4649	S0	1019 d	20.4	6.6	344	0.16	9.62	9.2
	M60 ARP 116								
18	I1459	E4	1634	32.7	5.4	252:	0.18	10.96:	6.9

The slopes of the best-fitting power-law profiles and the resultant values of chi-squared are shown in Table 2 for core radii of 1 and 10 arcsec: the 4 arcsec fits lie between these values. These slopes are typically 0.4 flatter than those obtained by naively fitting a power law to the surface brightness outside the core. There is no clear correlation of the slopes with X-ray or optical galaxy luminosity. The deconvolved slopes are sensitive to changes in the core radius, especially for those galaxies with slopes close to 2 (the total flux is then dominated by emission from the centre of the galaxy). The core radius is in general poorly determined since it is unresolved by the IPC. We note that the slope is also very sensitive to the level of background subtraction. In the fainter

Table 2. Best-fitting parameters for the deconvolved IPC using models $A[1+(r/a)^2]^{-s/2}$, where a is the core radius in arcsec, as described in the text. The second column shows the total number of IPC counts and the third shows the number of bins used in the fitting, N . Also shown are the fits to the HRI data where these exist. NGC 4636 is not well fitted by such a model and shows an extensive core.

Galaxy	IPC		$a = 1$		$a = 10$		N	HRI		
	Counts	N	Slope	χ^2	Slope	χ^2		Core	Slope	χ^2
N315	470	10	2.2	13	≥ 2.5	≤ 16				
N1052	240	10	2.0	4.3	2.4	4.3				
N1316	190	10	1.9	3.0	2.3	3.6	15	5.2	1.7	10
N1332	250	10	2.1	13	≥ 2.5	≤ 14				
N1395	660	15	1.3	20	1.4	23				
N1399	1700	33	1.4	27	1.5	28				
N1404	310	13	2.0	16	≥ 2.5	≤ 20				
N1600	25	5	2.1	.03*	≥ 2.5	$\leq .05^*$				
N2300	30	10	1.7	2.7*	2.0	2.7*				
N2563	190	15	1.2	12	1.5	12				
N4374							20	7.0	1.7	21
N4382	420	15	1.3	30	1.4	32				
N4406	1200	15	1.0	11	1.1	10	12	26	1.2	21
N4472	3800	33	1.4	39	1.6	38	20	3.8	1.4	13
N4594	420	30	1.8	26	2.0	29				
N4636	610	33	1.6	41	1.7	42		Complex core		
N4649	850	10	1.9	28	2.4	32				
I1459	110	21	2.1	19	2.5	20				

* Too few counts for χ^2 statistic

galaxies, addition of a uniform count rate equal to the uncertainty in the count rate of the outer bins can produce a change in slope of ~ 0.4 . The slopes are therefore poorly determined but are mostly consistent with a slope between 1.4 and 2.2. The physical extent of the galactic gas may depend upon environment, for example it may be truncated by ram-pressure stripping.

HRI profiles were available of some of the brightest galaxies. The HRI has a spatial resolution of ~ 4 arcsec and so the data did not have to be deconvolved. As the instrument has a higher internal background than the IPC, only the inner parts of these galaxies were detected. We again fitted models of the form $A[1+(r/a)^2]^{-s/2}$ to the data, where a is now a free parameter, and the best fits are shown in Table 2. There is evidence for flattening of varying extent at the centre of the galaxies, with an extended core for NGC 4636 (see Stanger & Warwick 1986). As we discuss later, the HRI profiles were in good agreement with the IPC deconvolved profiles over the regions of overlap.

Table 3. (i) Galaxy name. (ii) Electron density (10^{-3} cm^{-3}) at the effective radius. (iii) Cooling time (10^9 yr) in the central bin. This would be reduced considerably if higher resolution binning was used. (iv) Cooling radius (kpc) – i.e. outer radius of region within which the cooling time is less than $2 \times 10^{10} \text{ yr}$. (v) X-ray luminosity ($10^{40} \text{ erg s}^{-1}$) within the cooling radius. (vi) Total mass of X-ray emitting gas ($10^9 M_{\odot}$) within the cooling radius. (vii) Mass deposited ($M_{\odot} \text{ yr}^{-1}$) within the cooling radius for method (i) and (viii) for method (ii) as described in the text.

(i) Galaxy	(ii) $n(r_e)$	(iii) t_{cool}	(iv) r_{cool}	(v) L_x	(vi) M_{gas}	(vii) \dot{M}_a	(viii) \dot{M}_b
N315	3	3.5	60	100.	41.	2.6	1.8
N1052	3	3.4	20	3.8	1.6	0.10	0.07
N1316	5	1.8	>24	>9.5	>3.2	>0.23	>0.17
N1332	4	3.4	17	3.4	1.2	0.09	0.06
N1395	3	3.7	>28	>7.5	>3.6	>0.19	>0.16
N1399	8	0.5	68	74.	35.5	3.0	2.2
N1404	8	0.9	30	23.	5.9	0.58	0.28
N1600	3	3.9	>36	>37.	>9.8	>1.6	>0.80
N2300	3	4.0	26	6.3	2.9	0.21	0.15
N2563	2	3.1	26	9.7	3.2	0.40	0.27
N4374	8	0.9	>24	>13.	>3.5	>0.38	>0.28
N4382	2	1.7	12	0.7	0.3	0.06	0.02
N4406	6	1.6	>30	>30.	>7.4	>0.87	>0.65
N4472	5	1.0	>72	>64.	>36.5	>1.8	>1.2
N4594	4	1.3	17	5.8	2.0	0.18	0.08
N4636	9	0.6	>24	>30.	>5.6	>0.81	>0.67
N4649	8	0.9	>18	>15.	>2.2	>0.51	>0.27
I1459	3	2.6	18	3.2	1.3	0.09	0.06

2.1 THE DEPROJECTIONS

We adopted distances for the galaxies using their redshift (or that of the surrounding group) corrected for Galactic rotation. We assumed $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and that our Virgocentric motion is small.

X-ray emissivity profiles were extracted from the surface-brightness data by a direct deprojection method (Fabian *et al.* 1981). This assumes that the gas distribution is spherically symmetric and treats it as a series of concentric shells. We rebinned the data into 60- or 72-arcsec bins in order that the resolution of the IPC was not important: we chose not to use deconvolved profiles because of the uncertainties in slope and core radius discussed above. Working inward, the contributions from the projected emission of outer shells of gas were successively removed.

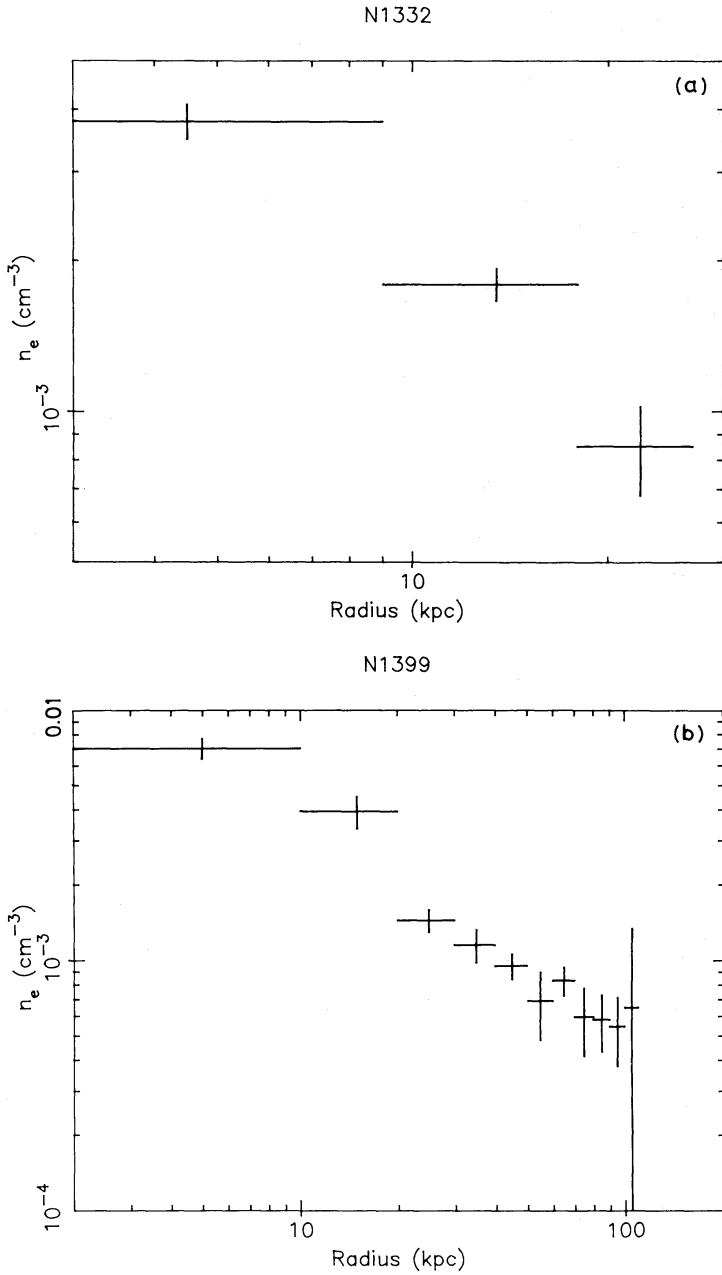


Figure 1. Electron density profiles for (a) a weak (NGC 1332) and (b) a strong (NGC 1399) source. The error bars show the dispersion generated by 100 perturbations, assuming Gaussian errors, of the count emissivity profile.

The resulting emissivity at each radius was converted to gas density and temperature using Raymond & Smith's (1977) bremsstrahlung and line spectra and including photoelectric absorption using values from the compilation of Galactic H I by Stark *et al.* (in preparation) and the cross-sections from Morrison & McCammon (1983). The pressure in each shell was evaluated from the equation of hydrostatic equilibrium. The only parameters required are the pressure in the outer shell and the gravitational potential distribution of the galaxy. This technique has been applied to X-ray data for many clusters of galaxies (e.g. Stewart *et al.* 1984; Arnaud 1985).

The thermal pressure of the gas in the outer shell was chosen so that the integrated emission appeared close to an overall temperature of 1.5 keV. (There are formally two solutions to the

temperature in each shell but the lower temperature is incompatible with this overall temperature.) Forman *et al.* (1985) and Trinchieri & Fabbiano (1985) estimate from IPC pulse height analysis that the temperature of the gas in the brighter galaxies is within ~ 0.5 keV of this value. The gravitational potentials of the individual galaxies were modelled with a de Vaucouleurs $r^{1/4}$ relation with effective radii from RC2 (de Vaucouleurs, de Vaucouleurs & Corwin (1976) and internal velocity dispersions from the compilation by Whitmore, McElroy & Tonry (1985). Four of the galaxies were not listed so we used the relation $\log \sigma = 0.328 - 0.0959 M_B$ (Terlevich *et al.* 1981).

2.2 DENSITY PROFILES

The deprojected density profiles are robust and do not depend strongly upon the temperature or gravitational potential although they do, of course, carry the uncertainties in the surface-brightness profile. We give the gas density at the effective radius for each galaxy in Table 3. A Monte Carlo simulation has been run to estimate the errors associated with these densities (Arnaud 1985). The surface-brightness profiles were perturbed 100 times to generate random rates statistically compatible with the original counts. The standard deviation of these deprojections was used as an estimate of the errors. We show the density profiles with these error bars for both a weak (NGC 1332) and a strong source (NGC 1399) in Fig. 1.

Density profiles were similarly produced from the HRI data using outer pressures taken from the IPC deprojections (except for M84 where no IPC data were available). Generally the HRI deprojections gave good agreement with the IPC, except in the cases of NGC 4636 and NGC 1316. The raw data for both are rather noisy and, as mentioned above, NGC 4636 has a complex core. NGC 1316 is the peculiar galaxy Fornax A and the poor agreement may indicate that the spectrum differs slightly from the others.

In Fig. 2 we show the density for the eight galaxies with the most extensive data. The error bars are those obtained formally from the counting statistics. All of the profiles are displayed together in Fig 3.

It can be seen from the figures and Table 2 that the densities at an effective radius lie within a factor of 3–4 of each other and that the density profiles have similar slopes. These slopes are relatively insensitive to the model parameters and can be estimated from the surface-brightness slope, s . In the temperature range of interest the emissivity varies approximately as $n^2 T^{-0.6}$, so that

$$n \propto r^{-(s+1)/2} T^{0.3}.$$

Thus, unless the temperature variation is extreme, we have a density slope of $(s+1)/2$. It has been pointed out by Cavaliere & Fusco-Femiano (1975) that, for an isothermal galaxy and gas, $\beta = (s+1)/6$ is the ratio of the galaxy to gas temperature. Our results give $0.4 \leq \beta \leq 0.55$ which is consistent with our chosen temperature for the gas. The similarity in β from one galaxy to another suggests that a similar mechanism operates in all the galaxies. This is reinforced by the small range of gas density at the effective radius. It is possible that the density of gas may build up until a balance is reached between the supply of gas and cooling to form new condensed objects as in the radiative regulation model by Cowie & Binney (1977). The gas then has a galactic origin, for example stellar mass loss.

2.3 MASS-DEPOSITION RATES

The radiative cooling time, t_{cool} , of the X-ray emitting gas is much less than a Hubble time across most of each galaxy. Therefore the gas is continually being removed from the flow and

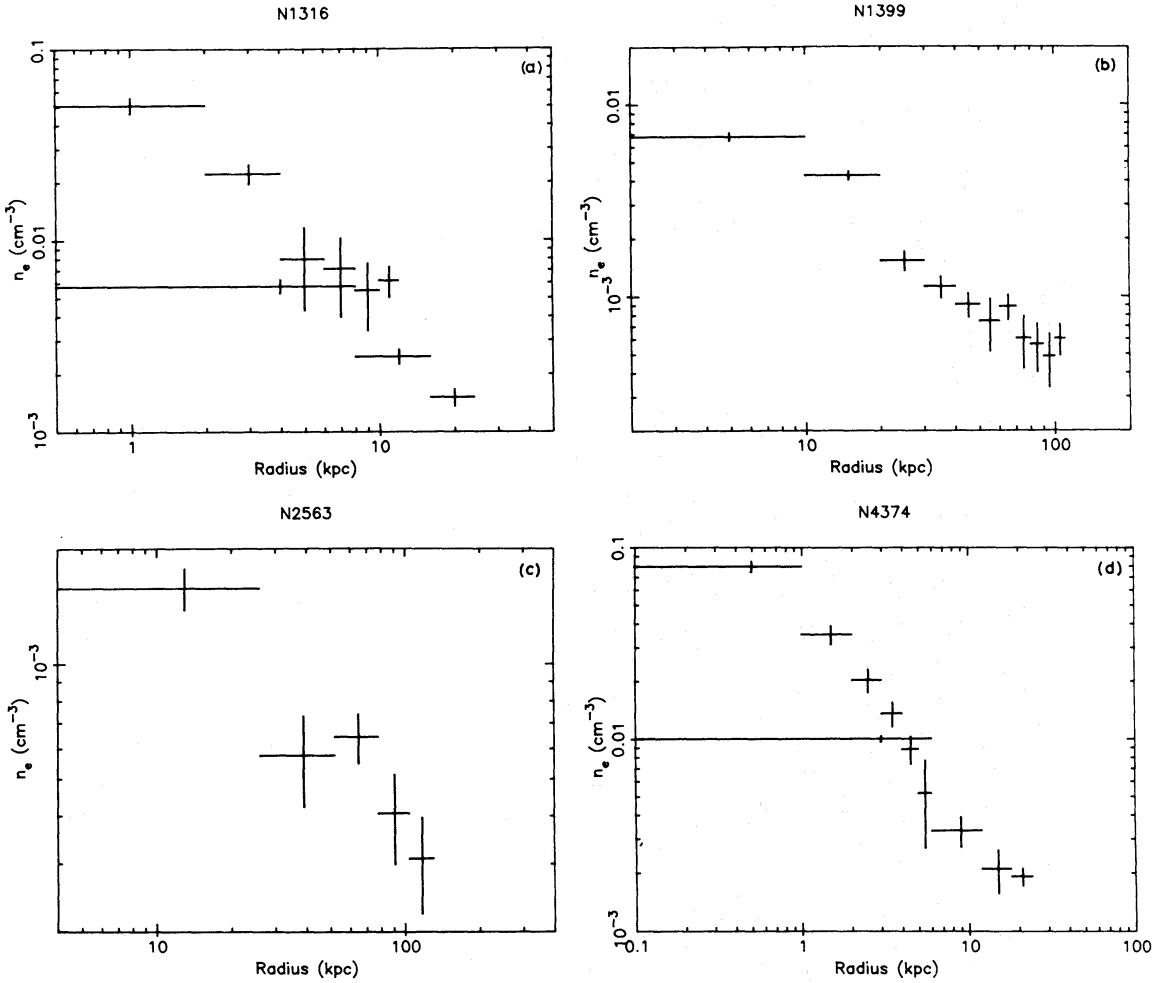


Figure 2. Electron density profiles for the eight most extensive galaxies. For those galaxies with more than one set of data the smaller bins are the HRI data. No IPC data were available for NGC 4374 and so the HRI was binned into 60 arcsec annuli in order to compare with the IPC observations of the other galaxies. The error bars are those obtained formally.

being replaced either by stellar mass loss or inflow. No heating mechanism suggested so far is able to overcome the thermal instability of the hot gas.

If the gas at each radius is perfectly homogeneous and of uniform density, cooling causes it to flow into the core of the galaxy where it produces a bright peak in the X-ray emission. This is not observed. Gas injection and other processes will, of course, make the gas inhomogeneous. Thermal instability then causes matter to cool out at all radii $r < r_{\text{cool}}$, where $t_{\text{cool}} \leq H_0^{-1}$ (Fabian *et al.* 1986; Nulsen 1986). We consider three ways in which this might happen:

(i) There are no radial flows, so that all gas present within the i th shell of width Δr originated there (e.g. from stellar mass loss) and cools and is deposited there at a rate

$$\Delta \dot{M}_a^i = \frac{\Delta L_i}{H_i},$$

where ΔL_i is the luminosity within Δr and H_i is the enthalpy ($5kT/2\mu m_H$).

Then $\dot{M}_a(r) = \sum \Delta \dot{M}_a^i$ is the rate at which mass is injected into and cools from the hot gas

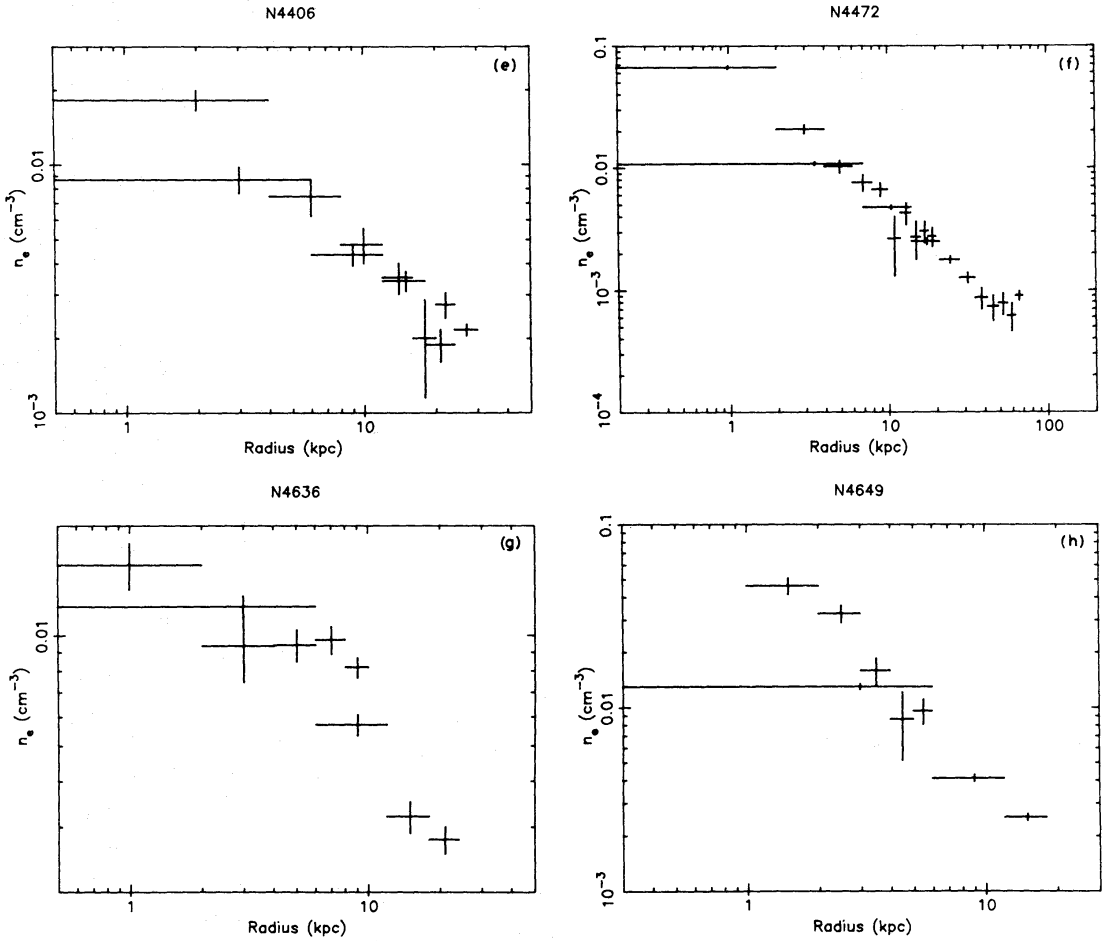


Figure 2-continued

within radius r . Note that the surface brightness in this case should follow that of the stars giving $s=2$, $\beta=0.5$.

(ii) Two gas phases are present within each shell, one of which cools out and is deposited there (at a rate $\Delta \dot{M}_b^i$), the other flows in across Δr (at a rate \dot{M}_b^{i-1}), so

$$\Delta \dot{M}_b^i = \frac{\Delta L_i - \dot{M}_b^{i-1}(\Delta H_i + \Delta \phi_i)}{H_i + f \Delta \phi_i},$$

with the mass flow rate $\dot{M}_b = \dot{M}_b^{i-1} + \Delta \dot{M}_b^i$ equal to the mass-deposition rate within that radius. $\Delta \phi_i$ is the change in gravitational potential across Δr and f is a factor representing the manner in which $\Delta \dot{M}_b^i$ is deposited across Δr

$$f = \frac{6i^2 - 8i + 3}{12i^2 - 12i + 4}; \quad \text{Fabian et al. (1985).}$$

This approach is an attempt to represent a flow of gas from large radii in which thermally unstable gas drops out of the flow over a range of radii and, for example, applies well to clusters of galaxies. Gravitational work is done on the gas and so \dot{M}_b represents the minimum rate of cooling gas.

(iii) Two gas phases are present, and mass and energy injection take place. This is the most

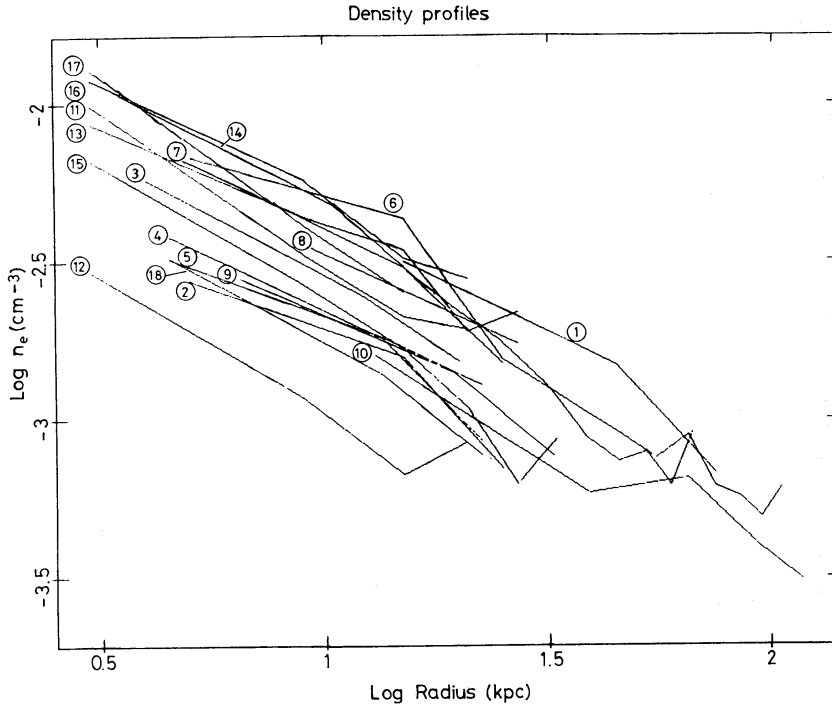


Figure 3. Electron density profiles of all the galaxies presented on the same plot for comparison. The number labels refer to Table 1.

realistic situation since stellar mass loss and supernova heating are expected, but it is the most difficult to model in a simple manner. Representing the mass cooling out within increment i as $\Delta \dot{M}_c^i$, the mass injection as $\Delta \dot{M}_+^i$, the mass outflow rate as \dot{M}^i , and including heating as enthalpy H_+ , we obtain

$$\Delta \dot{M}_c^i = \frac{\Delta L_i + \dot{M}^{i-1}(\Delta H_i + \Delta \phi_i) - \Delta \dot{M}_+^i(H_+ - H_i - f\Delta \phi_i)}{H_i + f\Delta \phi_i}$$

with the mass flow rate $\dot{M}^i = \dot{M}^{i-1} - \Delta \dot{M}_c^i + \Delta \dot{M}_+^i$. We assume that mass and heat injection are proportional to the observed stellar luminosity. Note that in this model the flow can be *outward* if H_+ is sufficiently high. Method (i) is essentially method (iii) with $H_+ = H_i$, $\Delta \dot{M}_+^i = \Delta \dot{M}_c^i = \Delta \dot{M}_a^i$ and $\dot{M}^i = 0$.

The total mass-deposition rates, $\dot{M}(r_{\text{cool}})$, within the cooling regions from the first two methods are given in Table 3. The mass flow-rate profiles are shown in Fig. 4. For all but two galaxies these estimates are less than the value ($\sim 1 M_\odot \text{ yr}^{-1}$) expected from stellar mass loss (Faber & Gallagher 1976), and in many cases they are significantly lower. In all cases the larger estimate of the mass deposited from the hot gas within the effective radius, $\dot{M}_a(r_e)$, is much less than the expected stellar mass loss, $\dot{M}_+(r_e) = \frac{1}{2} \dot{M}_+(\infty)$. This is shown in Fig. 5 (a) where $\dot{M}_a(r_e)$ is plotted against $\dot{M}_+(r_e)$. Fig. 5(b) shows $\dot{M}_a(r_{\text{cool}})$ against $\dot{M}_+(\infty)$. The formal error in the theoretical estimate of the stellar mass-injection rate is given as a factor of 3. Even if we reduced it by this factor, most of the galaxies would still deposit less than this amount of hot gas. We could reduce this discrepancy in part by reducing the gas temperatures (which, with the use of $3kT/2\mu m_H$ rather than $5kT/2\mu m_H$, would explain the difference between our result for \dot{M} in NGC 1395 and that of Nulsen *et al.* 1984). We are unable to find such solutions, however, since reducing the outer temperature does not substantially reduce the inner temperatures for the

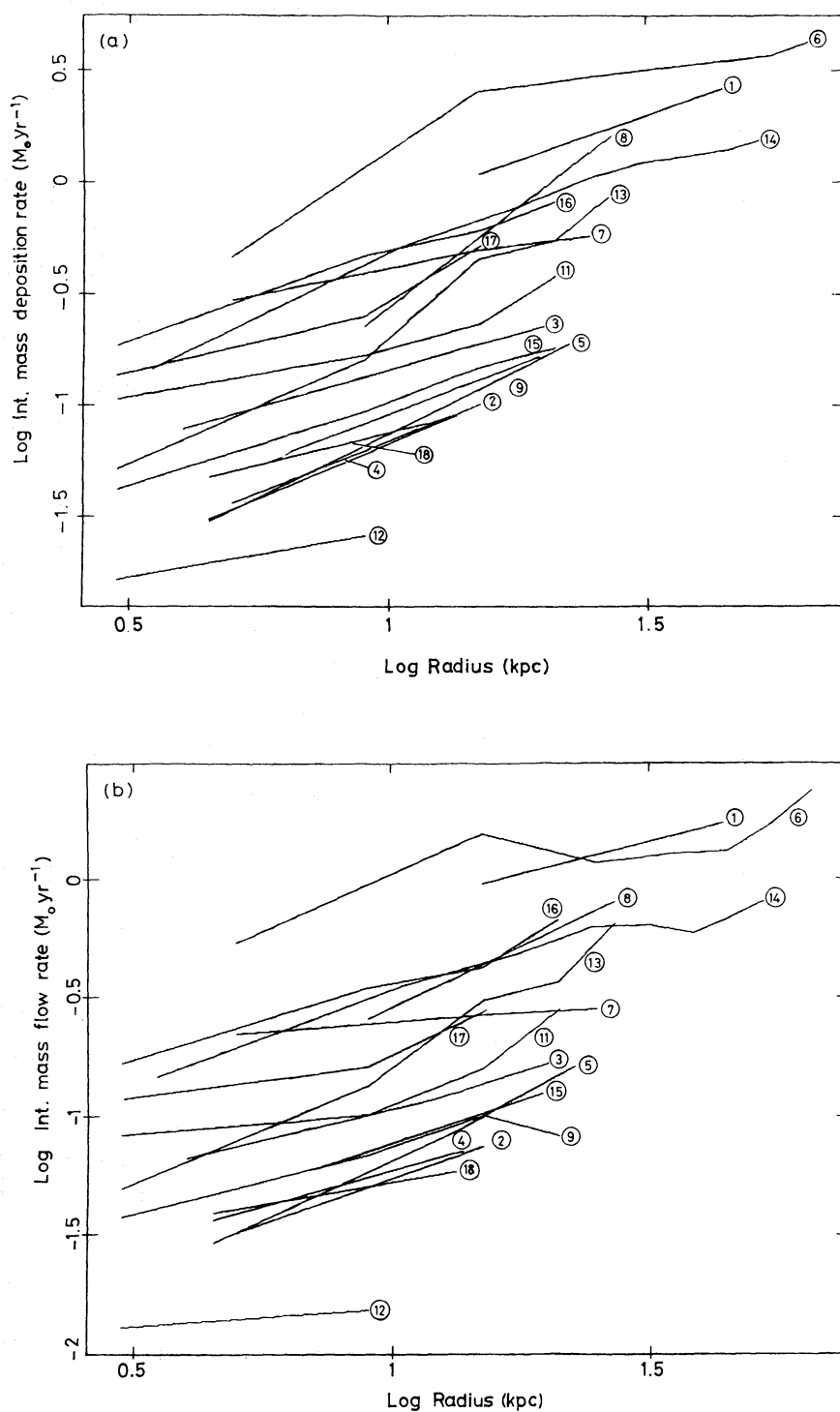


Figure 4. Integrated mass-deposition rates $\dot{M}(<r)$ from methods (i) and (ii) respectively. The number labels refer to Table 1.

assumed gravitational potential and detector response. A further problem which we, and others, have noted elsewhere concerns supernovae. If these inject 10^{51} erg at a rate similar to that estimated for early-type galaxies by Tammann (1974), then they supply more energy than is observed in X-rays (Nulsen *et al.* 1984; Thomas 1986; Fabian *et al.* 1986; Sarazin 1986; Canizares, Trinchieri & Fabbiano 1986). Note, however, that the supernova rate may be overestimated by a

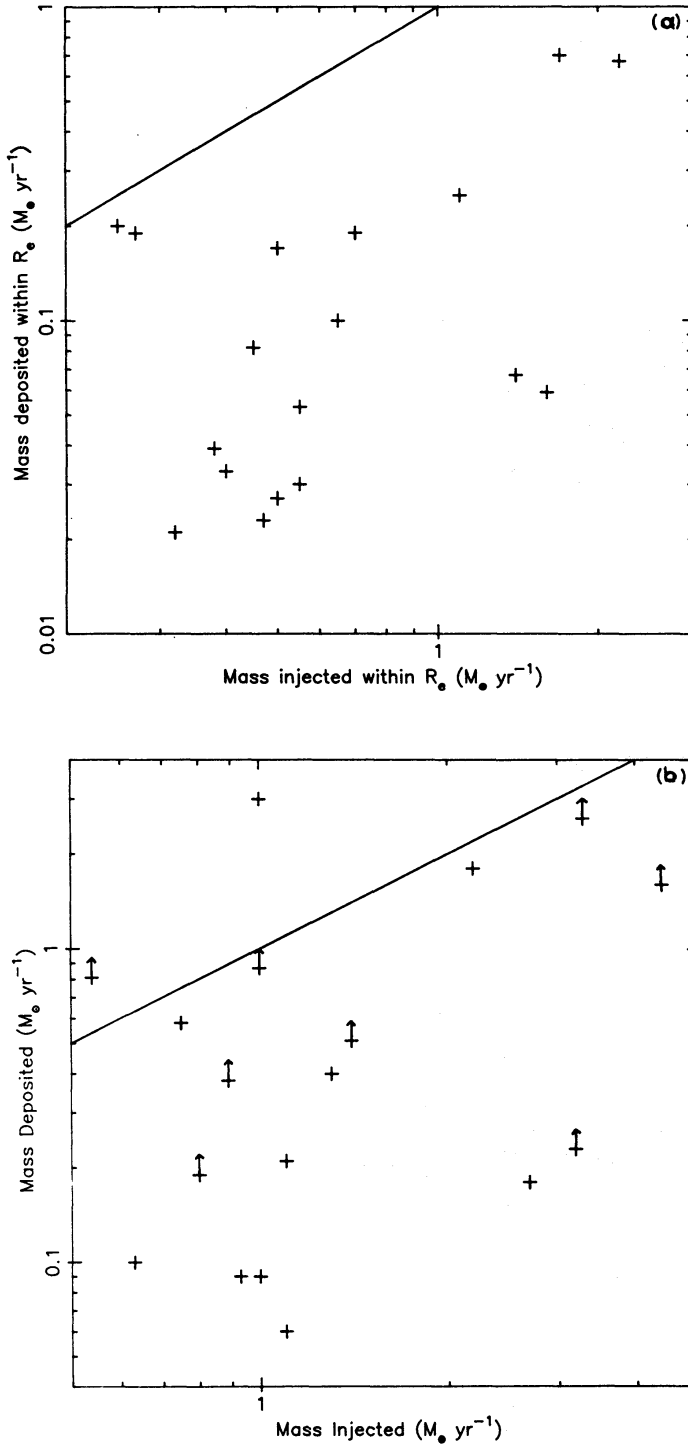


Figure 5. (a) Mass deposited within the effective radius (r_e) from method (i) versus the expected mass injection within r_e . $\dot{M}(r_e)$ is estimated by linear extrapolation from $\dot{M}(r_{\text{cool}})$ since Fig. 4 shows $\dot{M}(r) \sim r$. (b) Mass deposited within the cooling radius versus total expected mass injection.

factor of 10 or more in elliptical galaxies (Tammann, private communication). Similarly, any significant gravitational infall can overproduce the X-rays as can cooling if mass injection occurs at the predicted rate.

Method (iii) can overcome these difficulties by allowing the effects of supernovae (and any

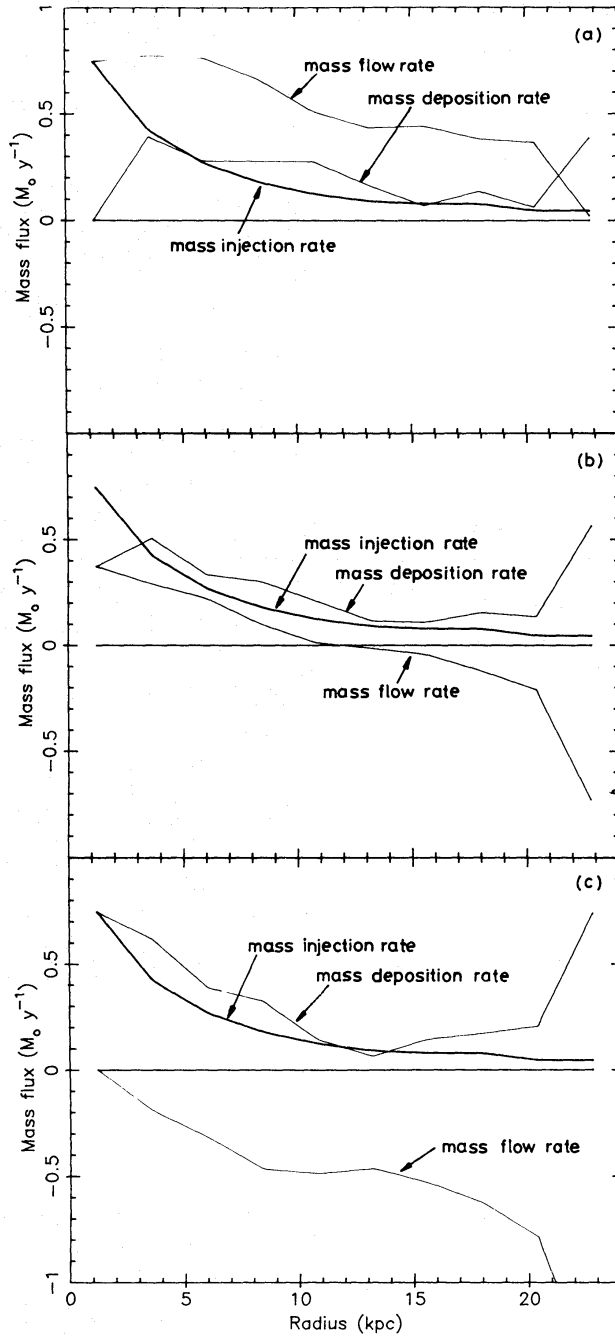


Figure 6. The result of applying method (iii) for determination of the mass-deposition rate to NGC 4472. A negative mass-flow rate refers to mass inflow. (a), (b) and (c) have injection temperatures of 2.4×10^7 , 1.4×10^7 and 4.4×10^6 K respectively, which, for a fixed mass-injection rate of $1.5 \times 10^{-11} M_{\odot} L_{\odot}^{-1}$ joining the flow, bound the possible solutions.

other) heating to be much reduced by making it do work against gravity by producing a cooling outflow. This is not really a wind, because little (if any) of the gas escapes. It is not a realistic model for a uniform gas, but, with the expected inhomogeneities present, different gas phases flow out to, and stagnate over, a wide range of radii. It is even possible that gas flows out of the inner regions and in from the outside. Further detailed work involving time-dependent multi-phase flows are needed to confirm this and check the stability of the overall flow pattern.

Fig. 6 shows the result of applying this method to NGC 4472. The energy-injection rate, i.e. H_+ , is varied whilst $\Delta\dot{M}_+^i$ is held fixed at $1.5 \times 10^{-11} M_\odot \text{yr}^{-1} L_\odot^{-1}$ (the rate predicted by Faber & Gallagher 1976). Inflow occurs throughout for low values of H_+ changing to outflow in the inner parts as H_+ is increased. We find that a supernova rate close to the predicted value of Tammann (1974) can be accommodated using this method. For the other galaxy with extended IPC data, NGC 1399, all solutions had inflow beyond the central bin. This is reflected in the high mass-flow rate – NGC 1399 is the only galaxy where this significantly exceeds the predicted mass-injection rate. For the galaxies whose cooling rates are much less than the predicted stellar mass-injection rate the gas will have to flow out a long way before cooling and it may be difficult to prevent a wind. This would result in a depletion of the hot gas to well below the detected values (Nulsen *et al.* 1984; White & Chevalier 1983). Alternative hypotheses are (i) that mass loss by stars is confined by the hot medium, is not heated to X-ray temperatures and so does not enter the flow considered here (White & Chevalier 1983; Thomas 1986; this is the motivation for considering method (ii) above), and (ii) that unusual events such as stripping or eruption of an active nucleus have cleared out much of the gas within the past central cooling time ($<10^9$ yr).

To summarize this section, we can state that cooling gas is common in most early-type galaxies and is deposited at rates between 0.02 and $3 M_\odot \text{yr}^{-1}$. In the most strongly detected galaxies a model involving inflow and/or outflow can account for the X-ray observations whilst allowing mass and heat injection into the hot phase at the predicted rates. If this pattern is considered unreasonable then either the mass- and heat-injection rates have been substantially overestimated, or mass lost from stars does not mix into the observed hot gas and supernova heat is not deposited there.

The low mass-flow rates inferred here mean that there will be little influence on the mass distribution of the galaxy over a Hubble time. It is of course possible that \dot{M} was higher in the past and that we are witnessing the tail-end of the formation of these galaxies. This may especially apply to those galaxies at the centres of groups, such as NGC 4472 and NGC 1399, where $\dot{M} \sim 1 M_\odot \text{yr}^{-1}$. Inflow or outflow of stellar-processed material will affect the chemical evolution of early-type galaxies.

3 Discussion

3.1 OPTICAL EMISSION

The central galaxies in cluster cooling flows, where $\dot{M}_{\text{cool}} \sim 10\text{--}100 M_\odot \text{yr}^{-1}$ or more, contain extensive optical emission-line filaments (Kent & Sargent 1979; Heckman 1980; Fabian *et al.* 1982a; Cowie *et al.* 1983; Hu, Cowie & Wang 1985). These generally indicate low ionization ($[\text{O II}] \gg [\text{O III}]$) and may be spread over a region of $1\text{--}10$ kpc in size. The filaments result from gas passing through the temperature range of $10^6\text{--}10^4$ K (see Cowie, Fabian & Nulsen 1980). Optical line emission has recently been found in a large fraction of early-type galaxies (Caldwell 1984; Demoulin-Ulrich, Butcher & Boksenberg 1984; Phillips *et al.* 1986). Several of the galaxies that we study here have well-known filamentation in their cores. NGC 1052 (Fosbury *et al.* 1979; Heckman 1980), and M84 have extended emission (Hansen, Norgaard-Nielsen & Jorgensen 1985) and NGC 1316 (Fornax A; Schweizer 1980) is a peculiar galaxy. All of these galaxies have dust lanes at the centre. NGC 1052 and 4315 have detectable H I emission (Shostak *et al.* 1983). Strong H I upper limits have been placed on several others (M86, Kotanyi & Ekers 1983; NGC 4382, 4472, 4636, Kumar & Thonnard 1983; M84, Shostak *et al.* 1983). The accretion of a gas-rich dwarf (Silk & Norman 1979) is often invoked to explain these properties. Cooled gas from the hot medium detected in X-rays is an alternative supply that does not require an external object. However, we cannot understand at this stage why some of the galaxies have very extensive

filaments and some do not (e.g. NGC 4472, van den Bergh & Pritchett 1985). The limits on optical line emission from early-type galaxies (e.g. Kennicutt & Kent 1983) do not rule out $0.1\text{--}1 M_{\odot}$ of gas cooling per year.

3.2 STAR FORMATION

We assume that the cooled gas forms into stars at a rate of about $1 M_{\odot} \text{yr}^{-1}$. Even if the low rates found from methods (i) and (ii) are appropriate, unmixed stellar mass loss presumably cools and collapses *in situ* at a similar rate. This means that the total rate of star formation in elliptical galaxies approaches the lower end of the range of $1\text{--}20 M_{\odot} \text{yr}^{-1}$ found in spirals (Kennicutt 1983). The detailed study of stellar populations in elliptical galaxies by Rose (1985) shows that star formation similar to that in the solar neighbourhood can be occurring now at rates which incorporate up to 50 per cent of the predicted stellar mass loss. The major diagnostics are some line ratios and the quantity of blue light from hot young stars. Unfortunately these can be mimicked by older horizontal branch stars (see also Gunn, Stryker & Tinsley 1981). This ambiguity turns the optical estimate of the ongoing star-formation rate into an upper limit.

It should not be surprising if the stellar initial-mass function were more skewed to lower masses than in the solar neighbourhood since the conditions, and in particular the pressure, in elliptical galaxies are more similar to those in cooling flow in clusters of galaxies. There the cooled gas must collapse into very low-mass objects ($M \ll 1 M_{\odot}$; Fabian, Nulsen & Canizares 1982b; Sarazin & O'Connell 1983).

3.3 INTERACTION WITH COLD GAS

We note that the hot interstellar gas in an early-type galaxy probably rotates in the same sense as the average orbit of a star since they are coupled through stellar mass-loss. The angular-momentum vector of the hot gas is thus in the same direction as that of the galaxy. On the other hand, cold gas which has enough angular momentum to orbit at an observable radius from the centre of a triaxial galaxy is restricted to certain stable orbits (Lake & Norman 1983; Merritt & de Zeeuw 1983). The angular-momentum vector of these stable orbits is typically perpendicular to that of the stars. (The stars orbit about the minor axis whereas cold gas orbits about the major axis.) The cold gas is then continuously impacted by the hot gas. The resultant torque will give the cold gas some of the angular momentum of the hot gas. Consequently, a cold gas disc in an early-type galaxy can develop a warp in the rotation sense of the stars. This can explain the shape of the dust lane in Cen A, which warps in the opposite sense to that expected from pure ballistic orbits but in the same sense as the galaxy rotation (Wilkinson *et al.* 1986).

3.4 ACTIVITY OF THE NUCLEUS AND PROPAGATION OF JETS

Several of our galaxies are well-studied radio sources, NGC 4374 (= M84 = 3C 272.1), NGC 1052, NGC 315 (which is a giant radio source 1.7 Mpc in size) and Fornax A (= NGC 1316). Only a small fraction of the mass-flow rate need reach the nucleus in order to power it by accretion. Cooling flows provide a simple internal source of fuel for an active nucleus. The gas density and pressure beyond the core may further be of importance in shaping and confining any radio jet (see e.g. Fomalont 1980; Sanders 1983; Perley, Bridle & Willis 1984; Begelman, Blandford & Rees 1984). M84 (Bridle & Perley 1984), NGC 315 (Willis *et al.* 1981) and Fornax A (Fomalont 1980) all show radio jets. Our thermal pressure profiles carry the gas temperature, and thus gravitational potential, uncertainty but are consistent with the general trends of the brighter galaxies (Fig. 7) where $p \propto r^{-\alpha}$, with $1.2 \leq \alpha \leq 1.6$, except in the core (≤ 10 arcsec) and at large

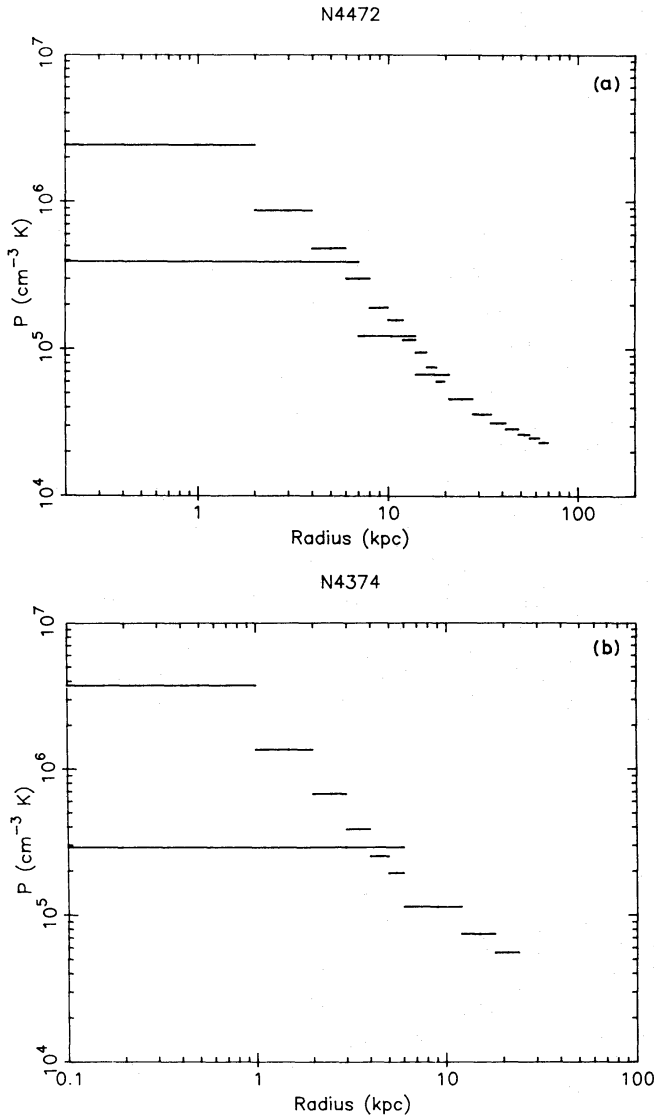


Figure 7. Pressure profiles for NGC 4472 and 4374.

radii where the environment and any massive also may be influential. The pressure along the length z of a free relativistic jet varies as $z^{-8/3}$ (Sanders 1983), so the slower decrease of the external pressure due to hot gas provides confinement over much of the galaxy. This confinement will, of course, lead to the production of internal shocks in the jet.

4 Conclusions

The early-type galaxies that we have studied contain a hot, X-ray emitting phase in their interstellar medium whose density varies as r^γ , where $\gamma \approx 1.2-1.6$. A similar result is obtained for Fornax A (NGC 1316) and for the bulge of the Sombrero galaxy (NGC 4594). These high densities lead to cooling flows with between 0.02 and $3 M_\odot \text{ yr}^{-1}$ condensing out of the hot interstellar medium. In the more X-ray luminous galaxies a combination of inflow and outflow can allow mass and energy injection at the rates expected from stellar mass loss and supernovae. In galaxies where the deposition rate is much less than the expected mass-injection rate, such a

model may not be feasible. Alternative explanations are either that little of the stellar mass loss enters the hot phase or that much of it has been lost from the galaxies in the recent past. Investigations of the time-dependent and multi-phase aspects of the interstellar medium in early-type galaxies should resolve this problem. Cooling flows account for the optical line emission observed in many elliptical galaxies. The total star-formation rate is about $1 M_{\odot} \text{ yr}^{-1}$ but the initial mass function may differ from that in late-type galaxies. Early-type galaxies may therefore contain some young stars. The hot interstellar gas provide a confining medium for radio jets and cooling inflows are an obvious source of fuel for an active nucleus.

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